

An integrated risk-based inspection approach for enhancing process safety in hydrocarbon storage tanks

Received: 18 May 2026

Accepted: 29 July 2026

Published online: 31 August 2026

Cite this article as: Kahoul H., Hellas M.S., Zerrouki H. *et al.* An integrated risk-based inspection approach for enhancing process safety in hydrocarbon storage tanks. *Sci Rep* (2026). <https://doi.org/10.1038/s41598-026-64995-7>

Hafida Kahoul, Mohamed Seddik Hellas, Hamza Zerrouki, Hemant Kumar, Sid Ali Bacha, Rachid Chaib & Shatrudhan Pandey

We are providing an unedited version of this manuscript to give early access to its findings. Before final publication, the manuscript will undergo further editing. Please note there may be errors present which affect the content, and all legal disclaimers apply.

If this paper is publishing under a Transparent Peer Review model then Peer Review reports will publish with the final article.

An integrated risk-based inspection approach for enhancing process safety in hydrocarbon storage tanks

Hafida Kahoul¹, Mohamed Seddik Hellas², Hamza Zerrouki², Hemant Kumar^{3*}, Sid Ali Bacha¹, Rachid Chaib¹, Shatrudhan Pandey^{4*}

¹ Laboratory of Transport Engineering and Environment, Frères Mentouri Constantine 1, University of Constantine, Algeria.

² Laboratory of Process Engineering, Materials and Environment, Amar Telidji University of Laghouat, Algeria.

³ Department of Mechatronics Engineering, Manipal University Jaipur, Jaipur, Rajasthan, India 303007

³ Marwadi University Research Center, Faculty of Management Studies, Marwadi University, Rajkot, 360003, Gujarat, India

**Corresponding author's e-mail: hemant.kumar@jaipur.manipal.edu (H. Kumar); er.shatrudhanp@gmail.com (S. Pandey)*

Abstract

Petroleum hydrocarbon releases from storage facilities represent a major environmental risk, particularly under harsh operating conditions where corrosion can compromise asset integrity. This study presents an integrated framework combining hazard analysis and Risk-Based Inspection (RBI) to improve the environmental safety of petroleum storage tanks. The methodology was applied to the SP1/RTI storage terminal operated by SONATRACH-TRC in In Amenas, Algeria, which comprises ten atmospheric storage tanks with a documented operational incident history. First, a systematic hazard study conducted by INERIS identified and ranked the hazardous phenomena associated with storage operations, providing an objective basis for equipment prioritization. Based on the resulting risk ranking, Tank A12 was selected as the most critical asset, and a routine visual inspection confirmed degradation mechanisms consistent with the identified hazards. Subsequently, an RBI assessment was performed using complementary non-destructive testing techniques, including Magnetic Flux Leakage (MFL) and Ultrasonic Testing (UT). The inspection revealed severe corrosion damage that substantially reduced the remaining service life of the tank and increased the likelihood of hydrocarbon leakage with potentially significant environmental consequences. Based on these findings, corrective maintenance was implemented in accordance with API 653 requirements, restoring the tank to safe operating conditions. The proposed framework demonstrates that integrating systematic hazard analysis with RBI enables objective asset prioritization, improves inspection planning, and supports proactive integrity management. This approach provides a practical strategy for reducing environmental risks and enhancing the long-term safety and reliability of petroleum storage facilities operating under severe environmental conditions.

Keywords: Storage tank, Environmental protection, Corrosion, RBI, Hazard analysis.

Nomenclature

Main Acronyms	
SONATRACH	National Company for Research, Production, Transport, Transformation, and Marketing of Hydrocarbons
REX	Experience-based Feedback
RBI	Risk-based Inspection
MFL	Magnetic Flux Leakage
FMECA	Failure modes, effects, and criticality analysis
API	American Petroleum Institute
PoF	Probability of Failure
CoF	Consequence of Failure

1. Introduction

Environmental contamination by petroleum hydrocarbons represents a major global concern due to their extensive use in transportation, industrial activities, and energy production. In addition to routine operations, accidental releases during exploration, extraction, storage, and transportation pose significant threats to ecosystems and human health. These incidents can lead to severe environmental degradation, affecting soil, water resources, and biotic components of ecosystems [1]. Within the process industry, ensuring the integrity and reliability of equipment is essential for maintaining continuous and safe operations. Maintenance and inspection activities play a crucial role in mitigating the risks associated with equipment degradation caused by operational conditions, environmental exposure, and aging. Various maintenance strategies have been developed in the literature, particularly in the downstream oil sector, where approaches based on equipment criticality, such as Analytical Hierarchy Process (AHP), Failure Modes, Effects, and Criticality Analysis (FMECA), and standards provided by the American Petroleum Institute (API), are widely applied to optimize maintenance planning and resource allocation [2][3].

Hydrocarbon storage systems constitute a critical component of oil and gas infrastructure, ensuring operational flexibility and supply continuity across the production, transportation, and distribution chain. These systems typically involve the temporary storage of fluids in tanks or pressure vessels, where processes such as phase separation, removal of impurities, and quality control are conducted before transportation or refining [4][5]. However, during storage, tank materials, primarily metallic structures, are continuously exposed to aggressive internal and external environments, making them particularly susceptible to corrosion and other degradation mechanisms [6].

Corrosion remains one of the most significant challenges affecting the integrity of storage facilities, accounting for a substantial proportion of failures reported in the oil and gas industry. Its occurrence can lead to material loss, structural weakening, and, ultimately, loss of containment [7][8]. Such failures may result in hazardous events, including leaks of flammable or toxic substances, fires, and environmental pollution. Consequently, corrosion not only compromises operational safety but also generates considerable economic losses and environmental liabilities

[9]. A comprehensive understanding of damage mechanisms is therefore essential for ensuring mechanical integrity [10]. These mechanisms, which include corrosion, cracking, and thermal degradation, depend on multiple factors such as material properties, process conditions, and environmental influences. Identifying and assessing these mechanisms enables the development of effective inspection strategies aimed at early detection and prevention of critical failures [10][11]. In this context, industry standards such as API 510, API 570, API 653, API RP 579, and API 580/581 provide structured frameworks for inspection, fitness-for-service evaluation, and risk-based inspection (RBI) [12][13].

Risk-Based Inspection has emerged as a powerful methodology for prioritizing inspection and maintenance activities based on the likelihood and consequences of failure. By integrating risk assessment with inspection planning, RBI allows for more efficient allocation of resources while maintaining high safety and reliability standards [14]. Despite its widespread adoption, conventional inspection approaches often remain limited by their static nature and insufficient consideration of dynamic degradation processes, particularly in aging infrastructure.

Indeed, a significant number of hydrocarbon storage tanks currently in operation have exceeded their initial design life, yet they continue to function under varying operational and environmental conditions. Aging infrastructure is increasingly prone to complex and interacting damage mechanisms, which may not be adequately captured by traditional inspection and maintenance frameworks [15][16]. This highlights the need for advanced methodologies capable of improving the accuracy of degradation assessment and supporting more reliable decision-making.

In this context, the present study aims to address these limitations by proposing an enhanced methodological framework for the assessment and inspection of hydrocarbon storage tanks. The proposed approach seeks to improve the identification and evaluation of critical degradation mechanisms while optimizing inspection planning to enhance safety, reliability, and environmental protection.

The remainder of the paper is organized as follows: [Section 2](#) presents the proposed methodology. [Section 3](#) describes the system under investigation and details the application of the approach. [Section 4](#) discusses the results and highlights the advantages and limitations of the method, including its application using Magnetic Flux Leakage (MFL) inspection. Finally, [Section 5](#) concludes the study.

1.1. Statement of novelty

With the rapid development of the petroleum and chemical industry, storage tanks play an increasing role in the storage of crude oil. However, these large-scale crude oil tanks have a high potential risk. Once the leakage of a large-scale crude oil tank happens, it not only causes serious environmental pollution, but also, in some cases, causes fire and even casualties.

The novelty of this study lies in the structured integration of a Hazard Study previously conducted on an operating petroleum facility (SP1/RTI, SONATRACH-TRC, In-Amenas Algeria) by INERIS (Report DRA-09-90194-00344A, January 2009), with a Risk-Based Inspection (RBI) framework applied within a real industrial case. This integration demonstrates how hazard study outputs can serve as direct inputs to RBI methodologies, thereby strengthening both the scientific

rigor and the operational relevance of inspection programs in the oil and gas sector. Importantly this work goes beyond a theoretical application: the RBI driven inspection of Tank A12 confirmed severe corrosion damage which led to its effective rehabilitation by SONATRACH. This real industrial outcome validates the entire integrated framework and closes the loop between hazard identification, risk assessment, and actionable integrity management decision-making. Overall, this study demonstrates the complete cycle from hazard prioritization through RBI application, to confirmed field intervention, within the specific operational and environmental context of the Algerian oil and gas industry.

1.2. Statement of industrial relevance

This study has significant industrial relevance, particularly for the oil and gas sector, where storage tank failures represent a major source of environmental and safety risks. Managing corrosion integrity for tanks is a challenging and costly endeavor. In order to inspect tank floors, the tank's hydrocarbons are usually emptied from the tank, causing the tank to be out-of-service for an extended period of time. This process increases the monetary costs and significantly safety risk. Currently, internal inspection is widely used by the petroleum and chemical industry for the management of crude oil tanks. However, the Internal Inspection Method often results in two disadvantages for tank management.

On the one hand, due to the high-capacity of crude oil tanks, it is expensive and time-consuming to clear and inspect the tanks, which can influence the normal production of the oil depot. If the tanks without severe corrosion defects are opened to inspect, this process increases the monetary costs and significantly safety risk. On the other hand, if the tanks with high risk are not timely inspected and repaired, it will bring potential safety hazards, and crude oil leakage may happen.

RBI is an effective approach that supports informed decision-making and resource allocation. In this context, economic optimization achieved through RBI allows for reducing overall inspection costs and financial loss for business interruption while ensuring asset integrity and safety, as well as promoting environmental preservation through the mitigation of leak risks and the prevention of hydrocarbon releases.

2. Methodology

First, a Hazard Study was carried out at the SP1/RTI facility in In Amenas, identifying the hazardous phenomena associated with storage operations. The site comprises ten tanks (A1, A2, A4, A5, A7, A8, A9, A10, A11, A12), which share an identical structure and design. A routine visual inspection of the tanks revealed signs of degradation directly linked to the hazardous phenomena previously characterized by the EDD. Tank A12 was consequently designated as a priority asset. Then a Risk-Based Inspection (RBI) study was conducted on Tank A12, ensuring methodological consistency between the hazard identification phase and the inspection plan. A quantitative inspection was carried out using two complementary techniques: Magnetic Flux Leakage (MFL) testing validated by ultrasonic testing (UT) measurements. The RBI study results identified corrosion as the dominant degradation mechanism, significantly reducing the tank's service life and increasing the probability of leakage.

Finally, a corrective action plan was developed, and the tank was repaired in accordance with API 653 requirements.

A properly implemented RBI program categorizes individual pieces of equipment by their risks and prioritizes inspection efforts based on this categorization^[17].

This methodology is based on risk assessment and management of loss of containment in pressurized systems due to material deterioration of equipment within processing facilities. These risks are primarily managed through targeted equipment inspection, as shown in Figure 1.

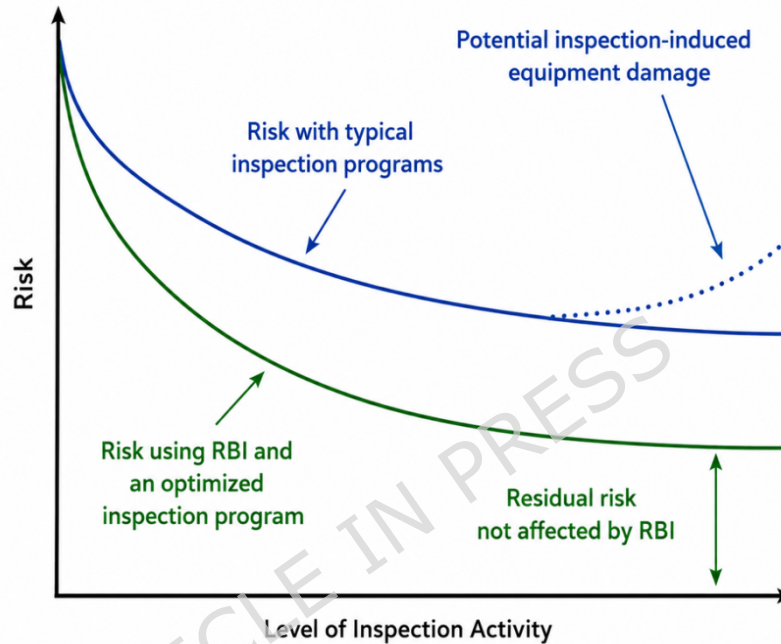


Figure 1. Management of risk using RBI ^[18]

Risk-Based Inspection is a dynamic, Systematic tool for prioritizing inspection according to the potential risk associated with specific equipment. RBI systematically evaluated both the probability of failure and the associated consequences of failure. The Risk-Based Inspection method is a strategic approach designed to optimize industrial inspections by identifying critical elements from safety and cost perspectives. By defining critical equipment and developing precise inspection plans ^[19].

This methodology enables:

- Reducing risks by enhancing the safety of personnel, facilities, and the environment,
- Maximizing the lifespan of equipment,
- Minimizing costly downtime of facilities

The implementation of an RBI methodology is a voluntary approach that enables the adaptation of procedures (frequency, type, and scope of controls) according to assessed risks (likelihood and consequences of failure). This methodology requires:

- Considering all relevant degradation mechanisms,

- Involvement of a multidisciplinary team bringing together the necessary expertise,
- Adherence to one of the following standards: EEMUA 159, API 580, API 581.

The following flowchart, as shown in [Figure 2](#), primarily describes the positioning of risk analysis in the RBI selected method flow process.

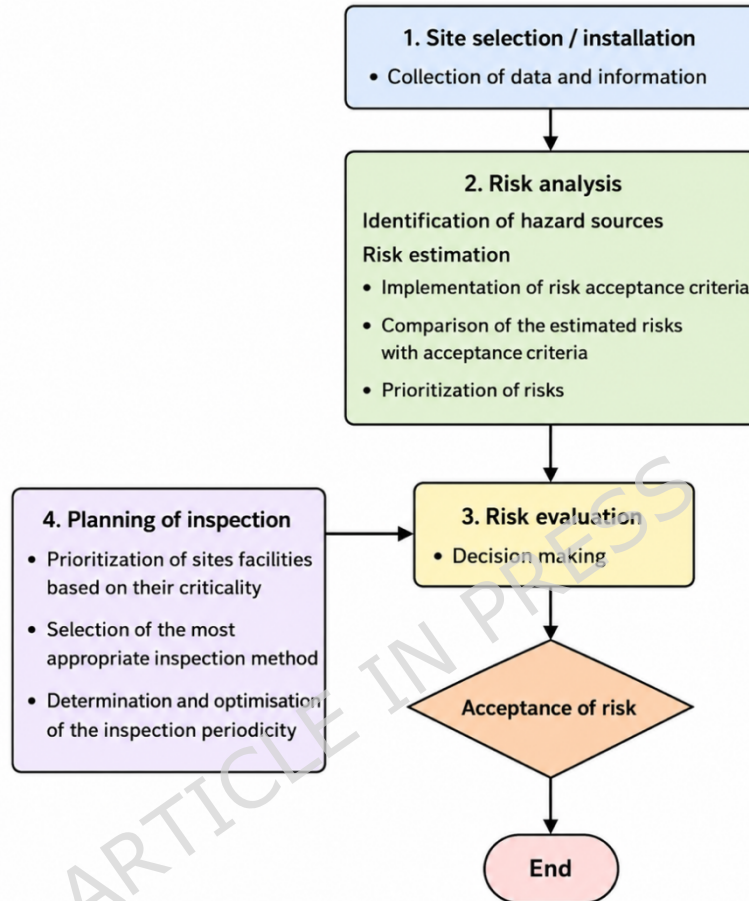


Figure 2. Risk analysis process and RBI approach [\[20\]](#).

The principles of RBI methodology:

- It formalises a consent approach
- It considers the Consequences and Likelihood of failure
- Identifies the highest-risk equipment
- Quantifies the risk
- Reflects the risk in the written scheme of examination

Risk-Based Inspection (RBI) analysis identifies critical facility components such as pressure vessels and piping, to focus inspection efforts where risks are highest. It requires a qualitative or quantitative assessment for each equipment item. Data related to equipment/components, operating conditions, damage mechanisms, inspection history, and more information will be collected. After the data is obtained, calculations will be carried out related to the probability of failure (PoF) and the consequences of failure (CoF). [Figure 3](#) shows a simplified block diagram of

the RBI process presented in API 580 (2016a). Determination of storage tank criticality based on the combination of the likelihood of a failure due to degradation and the consequence on the environment, health, and safety varies according to the part of the tank concerned. The analysis of the criticality is carried out for each of the three sections of the tank concerned (bottom, shell, roof). The overall criticality of the tank is the maximum criticality of each of the three sections; develop an inspection plan after calculating the next inspection interval according to the criticality, the confidence factor, and the residual life [21].

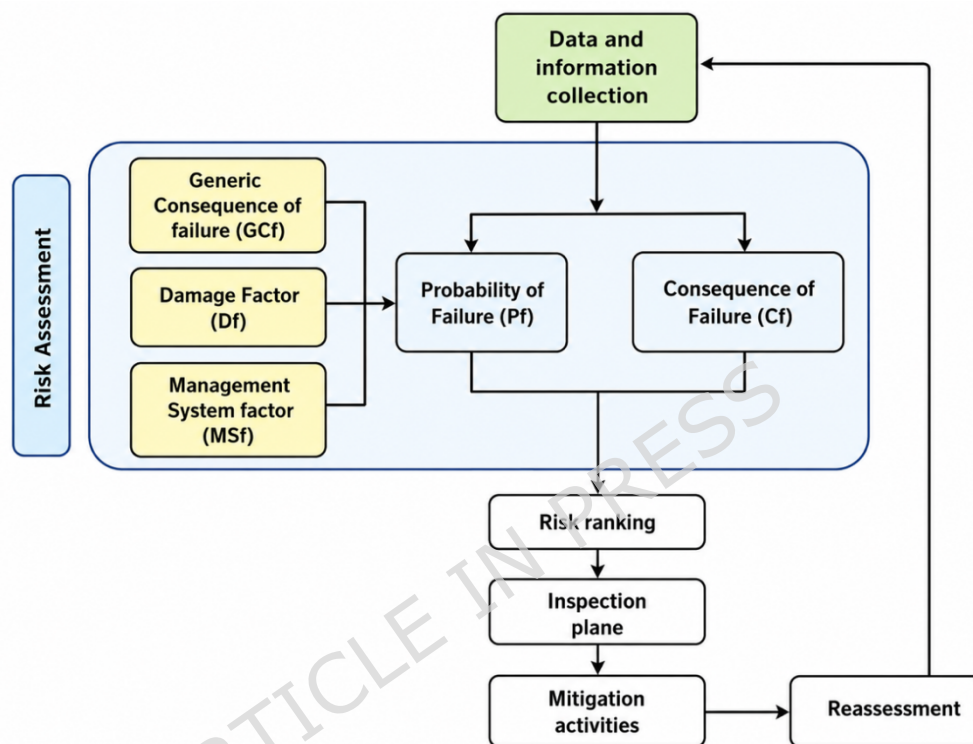


Figure 3. Block diagram of the RBI approach in API 580 [22].

3. Application

3.1. Description of the studied system (petroleum storage tank A12)

The A12 Tank, the focus of our study, is installed at the OH1/OT1 terminal of the SP1 station, in In-Amenas [Figure 4](#). Designed in accordance with API 650 standards, it has a capacity of about 18000 m³ and is used for atmospheric pressure crude oil storage at the production unit see [Figure 5](#).

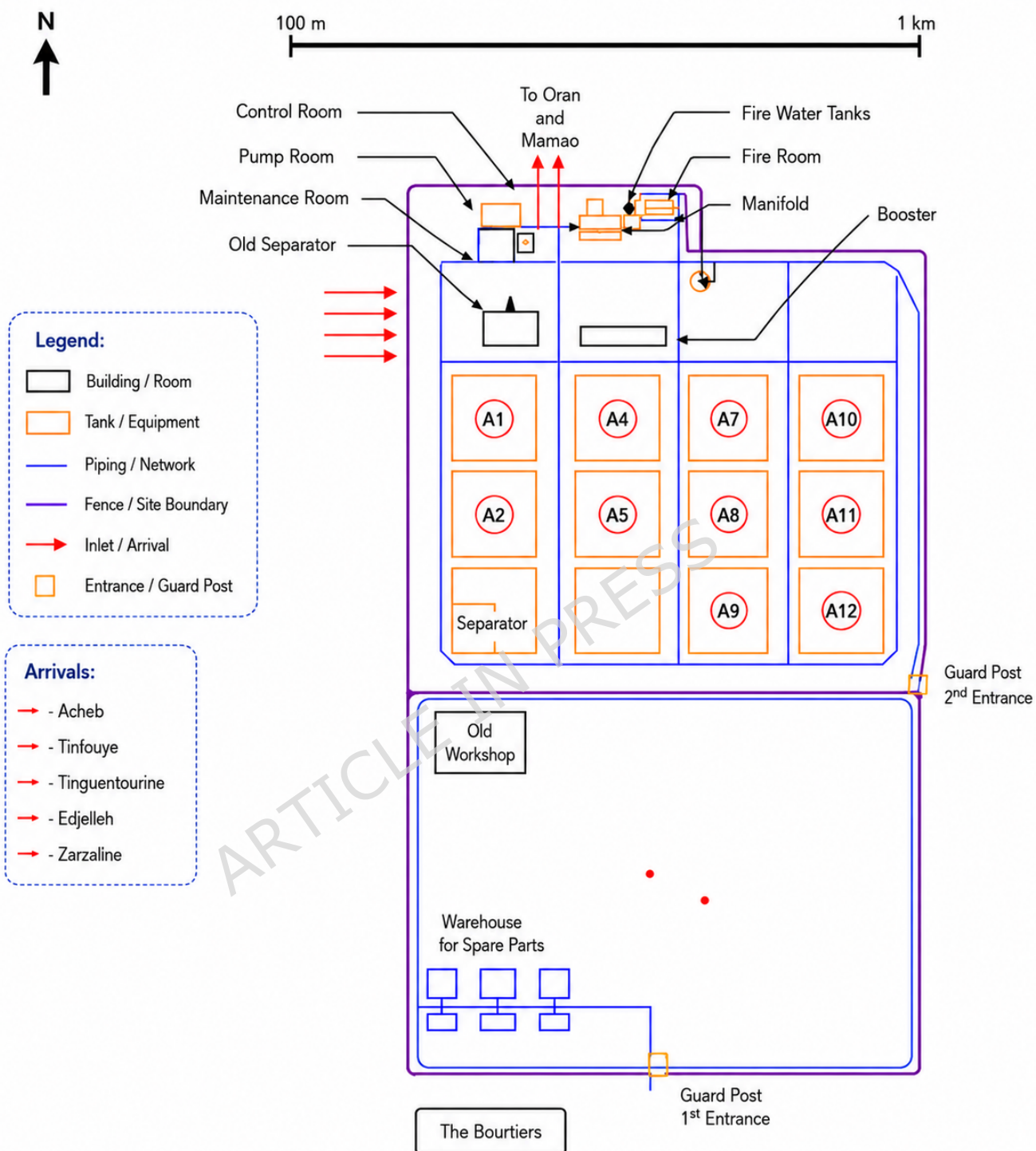


Figure 4. Ground plan of the OH1/OT1 terminal.



Figure 5. Oil storage tank A12.

The materials used in tanks are generally carbon steel, stainless steel, or composite materials, which can be employed to store certain chemicals. The choice of steel is determined based on the specific constraints of each component. The mechanical properties of the steel to be considered are defined in construction codes or, if unavailable, in repair codes. The principal characteristics of the Tank A12 are illustrated in [Table 1](#).

Table 1. Characteristics of the tank.

Site	SP1/RTI In Amenas
Identification	A12
Tank type	Atmospheric- Floating roof
Code used	API 650
Repair code	API 653
Year of construction	1961
Nominal Capacity	18000 m ³
Type of Fluid Stored	Crude
Nominal diameter (m)	45
Nominal height (m)	13
Operating temperature	Ambient
Operating Pressure	ATM
Material of construction	A283 Gr C
Plate nominal thickness (mm)	8

Number of Bottom Plates	163
Site	SP1/RTI In Amenas

In the present case study, leakage was identified as the primary failure mode, resulting from the corrosion of the tank. We selected an average annual leak frequency of 10^{-4}yr^{-1} , which is typical for storage tanks operating at atmospheric pressure. The leak is considered a potential initiating event capable of engendering a severe incident as a “pool fire.” The critical consequences include multiple fatalities, severe environmental pollution, and loss of containment, leading to industrial production interruption. Applying the risk matrix framework, the leak corresponds to a probability level P2 (Unlikely) and a severity level G4 (Catastrophic), characterized by several deaths, pollution exceeding acceptable limits for a prolonged duration, significant property damage, and complete shutdown of production. According to the risk acceptance criteria, this combination of probability and severity places the event in the "Unacceptable" risk category. This means that the risk posed by the leak and its potential consequences cannot be tolerated without the immediate implementation of effective risk mitigation measures. Table 2 presents the risk matrix for tank A12, adopted from SONTRACH, which maps quantitative (PoF) and (CoF) values to corresponding qualitative risk categories (Unacceptable, Tolerable, and Acceptable).

Table 2. Risk matrix adopted from SONTRACH

 Severity		CoF (Consequence of failure)				P1 Rare <10 ⁻⁴ yr ⁻¹	P2 Unlikely (10 ⁻⁴ -10 ⁻²) yr ⁻¹	P3 Likely (10 ⁻² -10 ⁻¹) yr ⁻¹	P4 Very likely 1 yr ⁻¹
		Personal	Environm ent	Public	Production/ Property				
Severity levels	G1 Minor	Minor injuries	Minor	No incidence	No damage, No down time	Acceptable	Acceptable	Acceptable	Tolerable
	G2 Moderate	Significant injuries	Internal pollution Controlled	Minor Injuries	Minor damage and short production downtime	Acceptable	Tolerable	Tolerable	Unacceptable
	G3 Severe (major)	Permanent disability or 1 death	Uncontrolled internal pollution	Significant Injuries	Localized damage and partial unit shutdown	Tolerable	Tolerable	Tolerable	Unacceptable
	G4 Catastrophic	Several deaths	Pollution out of limits of long duration	Deaths	Significant damage and total shutdown of production	Tolerable	Unacceptable A12 	Unacceptable	Unacceptable

3.2. Visual inspection

To assess the technical condition of storage tanks a visual routine inspection at the crude oil unit was conducted. This inspection method assesses equipment condition through visual examination for surface corrosion and metal corrosion [26]. In most cases, this preliminary inspection detects

only major defects visible to the naked eye [27-29], conducted in accordance with API 653 guidelines, the visual inspection covered 100% of the surface area and revealed that corrosion was a recurrent issue, manifesting in various forms and variable sizes across multiple plates, as shown in Figure 6 (a-c). Based on these observations, equipment's age and inspection history, the unit's technical team identified Tank A12 as critical asset

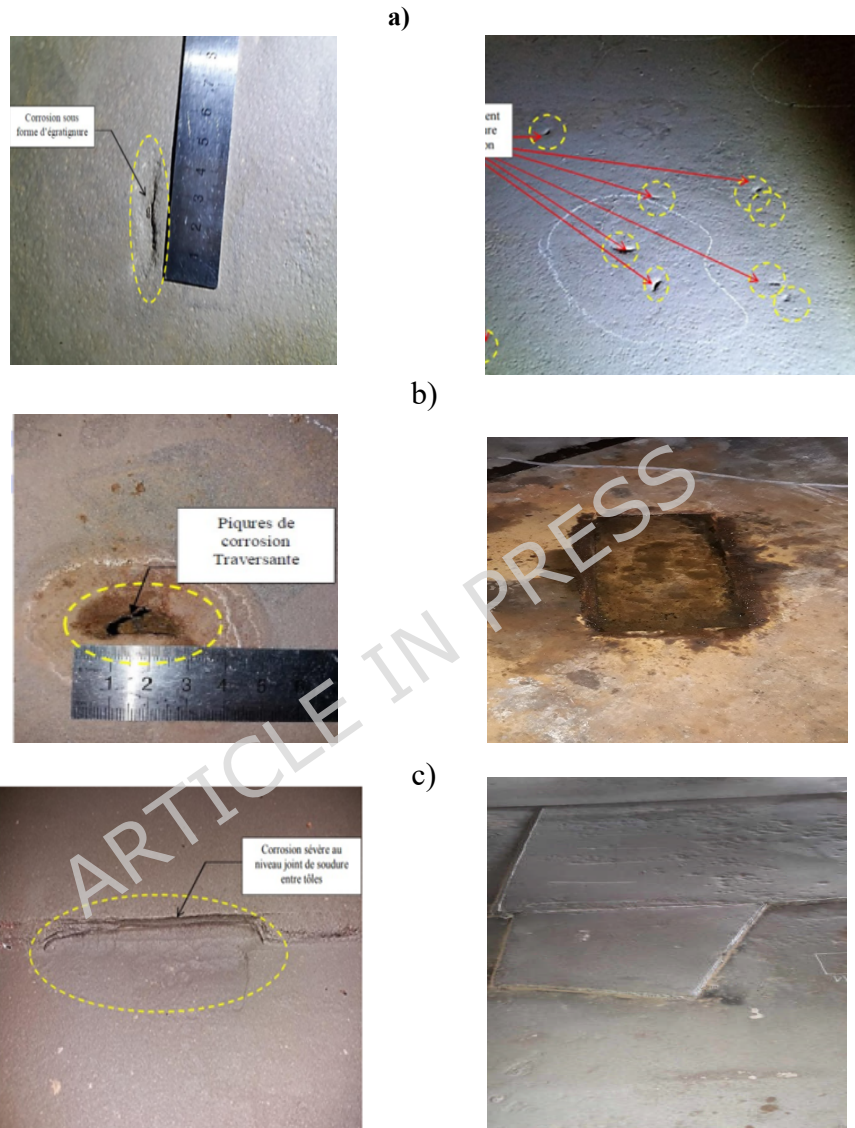


Figure 6. Visual inspection (a) Corrosion in the form of scratches (b) Through wall pitting corrosion (c) Corrosion at Weld joint – non compliant patch

Key observations included:

- A significant number of pits (localized corrosion) of varying depths were visible on multiple bottom plates.
- A considerable number of perforations due to internal corrosion (localized on sun exposed sides) were visible on several plates as well as on weld seams.

- Several patch plates, the shape of which does not meet API 653 requirements, were observed. The 860 defects quantified during the inspection as indicated in [Table 3](#). are distributed as follows:
 - The presence of 434 pitting defects (212 light + 222 severe) of varying depths is the direct signature of active localized corrosion,
 - The localization of 209 through perforations on sun-exposed faces
 - The presence of 142 defects specifically localized on welded joints
- The defects are:

Table 3. Identification of type of defects.

Light	Severe	Through	Welding joint	Other defects
212	222	209	142	75

The analysis revealed that severe corrosion constitutes the most dominant failure mode, accounting for 26% of cases. Both light and through wall corrosion indicate a rate of 25% respectively. Weld joint corrosion constitutes 16% of the total damage, which is particularly critical given the role of weld integrity in ensuring the tank's structural resilience. Other types of corrosion account only for 9% see [Figure 7](#).

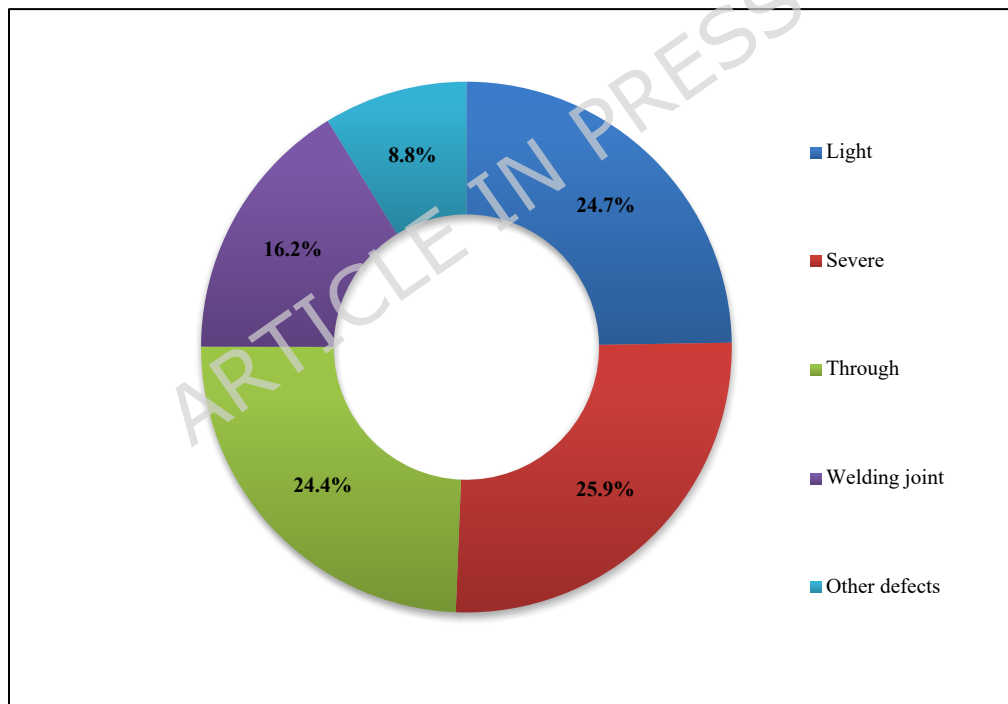


Figure 7. Distribution of defects.

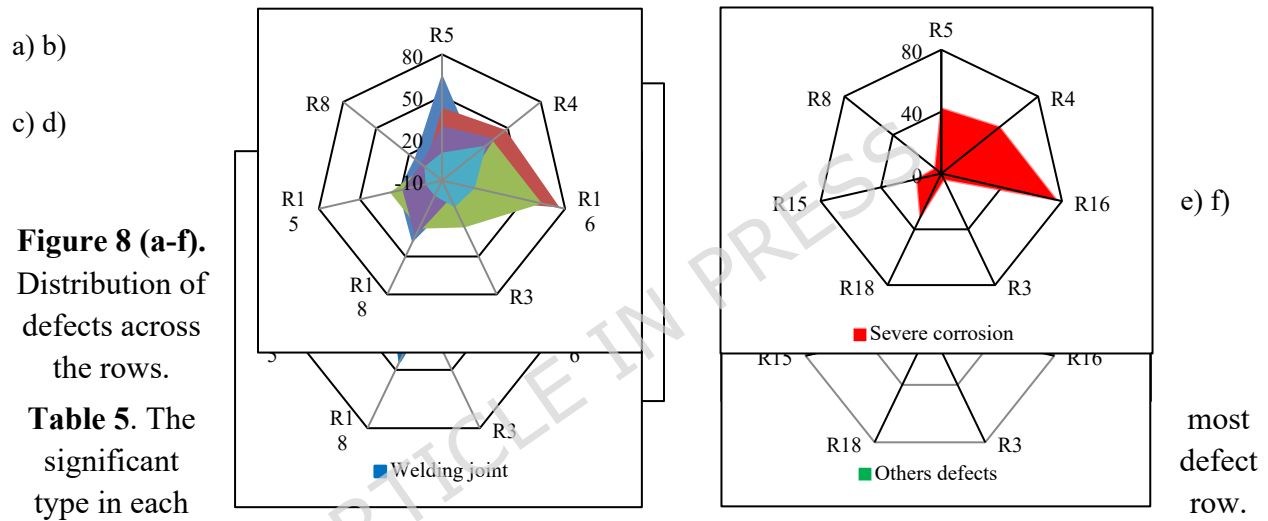
For further analysis, some rows with thickness losses exceeding 81 (%) were selected as shown in [Table 4](#). Moreover, [Table 5](#) summarizes the most significant defects identified in each row.

Table 4. Identification of rows.

R	RÉ F	P	Measure d thickness	Positio n X (cm)	Positio n Y (cm)	Thicknes s at defect	Defect locatio n	Loss of thicknes s	Loss of thickness (%)
---	------	---	---------------------	------------------	------------------	----------------------	------------------	--------------------	-----------------------

			(mm)			level (mm)		(mm)	
R3	BL	P18	9,17	64	18	1,68	T	7,49	81,69
R4	BL	P24	8,60	51	15	1,34	B	7,26	84,41
R5	BL	P30	8,726	611	38	1,53	T	7,20	82,47
R8	BL	P50	9,00	403	23	1,7	T	7,3	81,11
R15	BL	P10	8,98	448	93	1.65	B	7,10	81,15
		2							
R16	BL	P11	9,40	704	62	1,38	B	7,49	84,44
		3							
R18	BL	P12	8,80	32	46	1,57	B	7,23	82,16
		4							

The distribution of defect types across these rows is presented in Figure 8 (a-f).



Row	Light	Severe	Through	Welding joint	Others	Total
R5	18	17	2	12	1	50
R4	15	17	12	13	3	60
R16	19	24	12	8	9	72
R15	7	4	16	3	8	38
R18	14	5	13	15	1	48
R3	9	9	10	7	2	37
R8	4	6	3	5	1	19

The most significant defect types across the rows are illustrated in Figure 9.

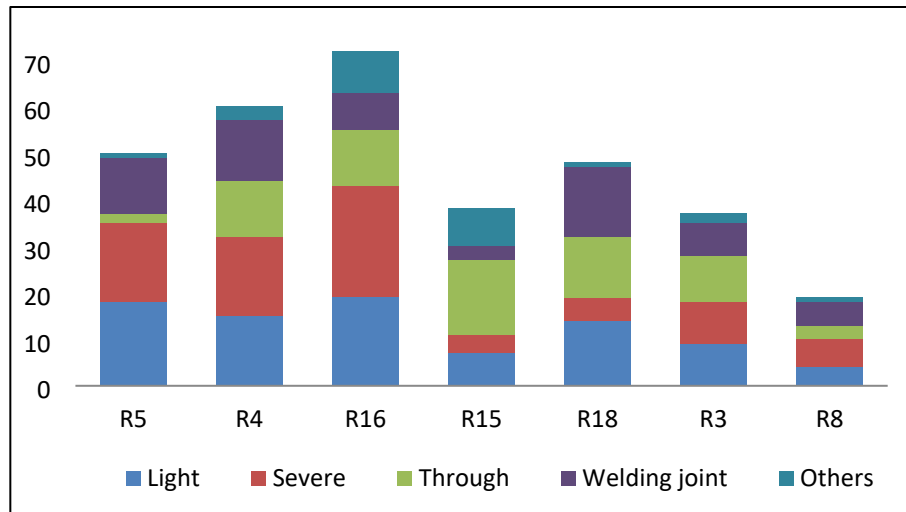


Figure 9. Distribution of the most significant defect type in the rows.

Using the Vilfredo Pareto principle, an additional analysis was conducted to identify the rows with the most significant defects, see [Table 6](#).

Table 6. Classification of types of defects by the PARETO principle.

Row	Corrosion type	Total defects	%	% Cumulus
R16	S	24	23%	23%
R4	L	18	17%	41%
R5	S	17	17%	57%
R18	L	16	16%	73%
R3	TH	14	14%	86%
R15	TH	10	10%	96%
R8	L	4	4%	100%

The extent of corrosion along the rows is illustrated in [Figure 10](#). The latter shows the distribution of corrosion defects on the tank's bottom plates, revealing that 80% of defects are classified as severe, light, and concentrated in five critical rows (R16, R4, R5, R18, and R3).

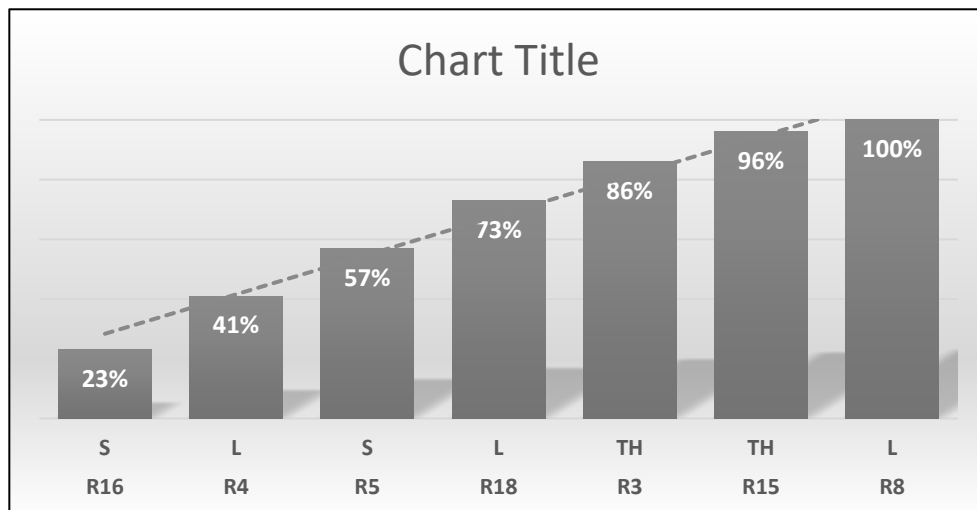


Figure 10. Pareto diagram.

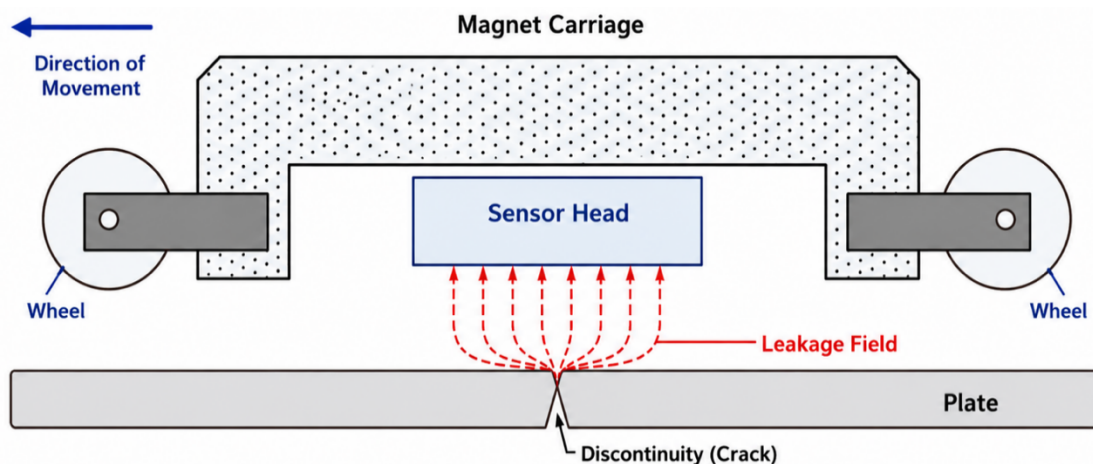
3.3. Inspection Methods

Material degradation often results from environmental factors that promote internal corrosion, such as climatic conditions and the nature of the stored fluid. It is commonly assumed that leaks are an early warning sign of major failure, which often focuses attention on areas of wall thinning. However, critical failures can occur without any prior leak detection. Therefore, it is essential to employ advanced inspection techniques and specialized equipment capable of detecting early signs of degradation, major failure risks, and corrosion forms responsible for leaks. For fast detection of the corrosion, the crude oil unit used two complementary techniques magnetic flux leakage (MFL) and ultrasonic testing (UT) measurements [23], [24], [25].

3.4. Magnetic flux leakage (MFL)

Magnetic flux leakage is an advanced electromagnetic non-destructive testing technique used to inspect ferromagnetic metal plates of storage tanks for corrosion detection. This effective preventive method ensures optimal structural and environmental safety.

The MFL method uses a powerful magnet to magnetize the conductive material under test. If any discontinuity exists in the material, like corrosion or material loss, the magnetic field “leaks” from the material. MFL probes incorporate a magnetic detector placed between the poles of the magnet, where it can detect the leakage field. The magnetic field induced in the material (plate) saturates it until it can no longer hold any more magnetic flux. The magnetic flux overflows and leaks out of the plate, and strategically placed sensors can accurately measure the three-dimensional vector of the leakage field. Flux Leakage is a qualitative, not quantitative inspection tool. It is very good at detecting magnetic anomalies and covering the very large floor areas of tanks very quickly. It is not, however capable of the accurate quantification of the signals as regards the remaining wall thickness. The amplitude of the signals is a function of the volume loss of material rather than a measure of the thickness loss. Accept/ reject criteria based on only amplitude of the signal can lead to significant defects going undetected. Figure 11 illustrates the basic principle of the MFL method.

**Figure 11.** Magnetic Flux Leakage (MFL)

4. Ultrasonics (UT)

Ultrasonic testing is a non-destructive testing method based on the transmission, reflection, and absorption of an ultrasonic wave propagating through the part being inspected, enabling the detection of defects both within the material's volume and on its surface.

Figure 12 illustrates a simple UT set-up using the pulse-echo principle and a twin crystal probe. In this configuration one crystal acts as transmitter and the other as the receiver. The transmitter is isolated from the receiving circuits so that the A-scan display is freed from the presence of a transmission signal. As a result, the transmission pulse does not obscure the first back wall echo when testing relatively thin areas of plate or pipe. We shall see that simple digital thickness meters without an A-scan facility are not suitable for either detection or measurement of pitting.

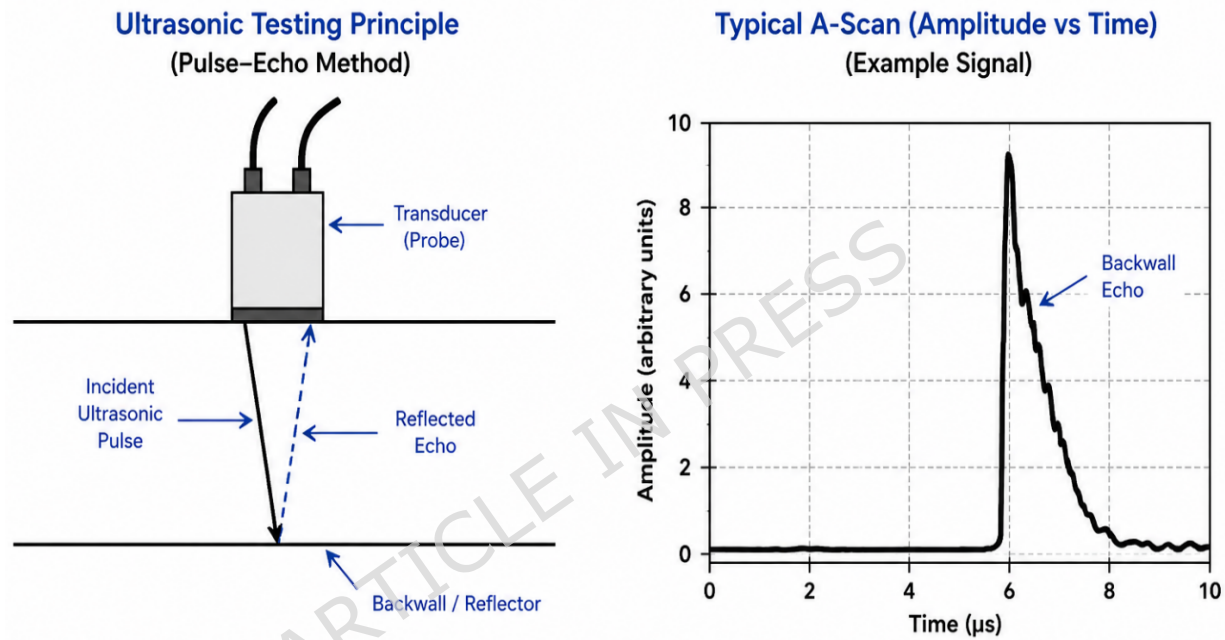


Figure 12. Manual Ultrasonics testing (UT)

an amplitude-depth response curve was established in accordance with the requirements of ASTM E570 §8 and API 653. According to API 653, the minimum allowable thickness of the tank bottom must not fall below 2.5 mm. This threshold applies specifically to all critical defects areas where metal loss exceeds 60% of the nominal thickness of bottom tank. This value represents the structural integrity threshold below which the bottom plate can no longer guarantee resistance to operational loads and corrosion degradation. Any critical thickness loss exceeding 60% was validated by conventional ultrasonic testing (UT) any measured wall thickness loss exceeding 60% was checked by ultrasonic testing (UT) GE DM5E thickness Gauge

5. Results and discussion

In the present study, the nominal thickness of the bottom plates was 8 mm. The defect assessment conducted during this inspection revealed that, among the 163 plates examined, 99 plates (61%) exhibit thickness values approaching the limit of 2.5 mm, and 38 plates (23%) present remaining thickness below the required threshold. Only 26 plates (16%) remain at an acceptable thickness.

Consequently, a significant number of plates will require corrective actions, including repair or full replacement in accordance with API 653, to ensure safety and prevent further deterioration that could compromise the structural integrity of the tank.

Given the large number of measurements (163), thickness measurements at the indications identified by MFL inspection are provided only for some of them, to highlight specific findings. The selected values are presented in [Table 7](#).

Table 7. MFL measurements

R	RÉF	P	Measured thickness (mm)	Position X (cm)	Position Y (cm)	Measured Thickness at the defect level (mm)	Defect location	Loss (mm)	Loss (%)
R1	BL	P3	9,02	151	224	1,72	T	7,30	80,93
R1	BL	P8	8,37	48	51	2,13	T	6,24	74,54
R2	BL	P13	8,99	323	20	2,17	T	6,82	75,85
				456	95	2,37	T	6,62	73,63
R2	BL	P14	9,65	220	47	2,10	T	7,55	78,23
R2	BL	P15	8,58	244	124	2,30	B	6,28	73,19
R3	BL	P18	9,17	64	18	1,68	T	7,49	81,69
				688	85	2,34	T	6,53	73,62
R3	BL	P19	8,87	700	128	1,64	T	7,23	81,51
				704	62	1,38	B	7,49	84,44
R4	BL	P23	9,19	308	38	2,2	T	5,79	74,41
R4	BL	P24	8,60	51	15	1,34	B	726	84,41
				266	25	1,55	T	7,05	81,97
				162	47	1,51	T	7,09	82,43
R5	BL	P28	9,00	121	136	2,46	T	6,54	72,67
				288	63	1,64	T	7,36	81,78
R5	BL	P30	8,72	23	81	2,26	T	6,47	74,10
				611	38	1,53	T	7,20	82,47
				444	55	2,32	T	6,41	73,41
				551	44	1,96	T	6,77	77,54
R6	BL	P39	8,77	52	47	1,91	T	6,91	78,35
R7	BL	P37	8,87	322	43	1,89	T	6,98	78,69
R7	BL	P41	8,67	20	49	1,86	T	6,81	78,35
				26	77	2,16	T	6,51	75,09
				103	128	1,83	T	6,84	78,89
R7	BL	P43	9,245	232	24	1,79	T	7,46	80,64
				235	69	2,4	T	6,85	74,04
				29	113	1,97	T	7,05	78,15
				120	51	2,23	T	6,52	74,51
				161	81	1,99	T	6,76	77,26
R7	BL	P45	8,75	198	45	1,82	T	6,93	79,20
				658	34	1,78	T	6,97	79,66
R7	BL	P46	8,96	242	27	2,24	B	6,72	75,00
R8	BL	P48	9,4	684	79	1,95	T	7,45	79,26
				564	62	1,82	T	7,58	80,64

R8	BL	P49	9,01	665	14	2,45	T	6,56	72,81
				631	47	2,02	T	6,99	77,58
				24	38	2,08	T	6,93	76,91
R8	BL	P50	9,00	403	23	1,7	T	7,3	81,11
R8	BL	P52	9,36	476	141	1,71	T	7,65	81,74
				465	115	2,21	T	7,15	76,40
				520	79	2,2	T	7,39	77,05
R9	BL	P57	9,59	533	90	2,7	T	6,89	71,84

T (TOP), B (BOTTOM), R (ROW), P (PLATE).

Taking into account the results of the MFL inspections, it is evident that a thickness loss exceeding of 60% of the measured thickness occurs over a significant range of the bottom surface. Moreover, a large number of defects are installed on the bottom of Tank A12, putting it in a critical situation. The scanning examination of the bottom plates using the (MFL) technique is presented in Figure 13 (a-b).

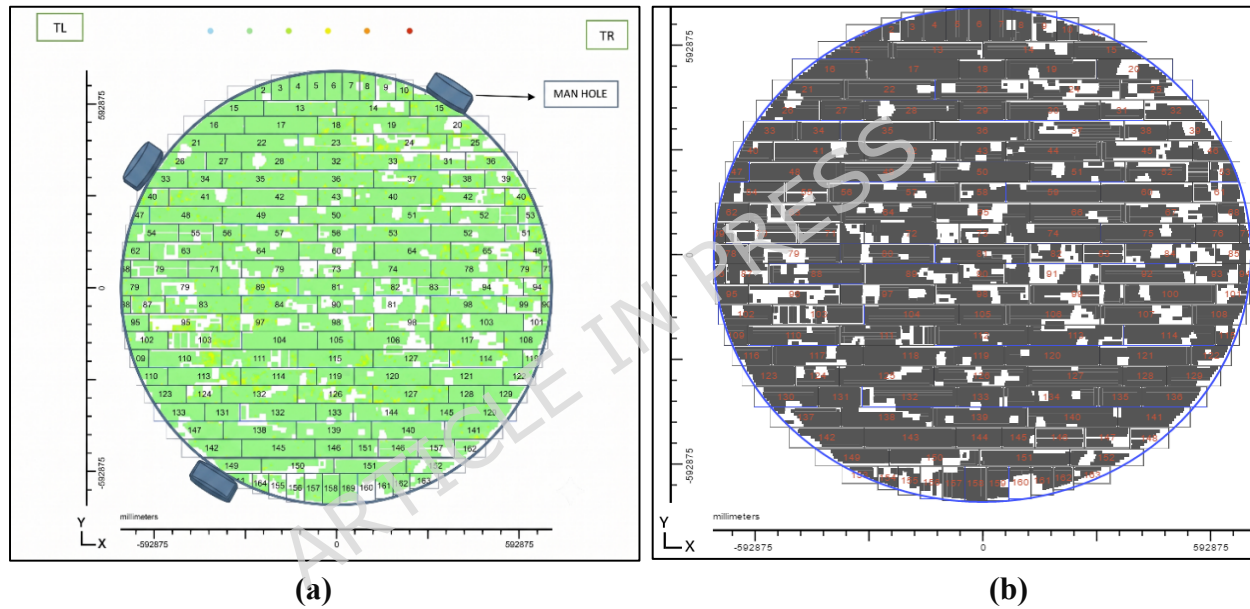


Figure 13. A12 tank floor MFL scan

Figure 14 presents the heatmaps of some critical bottom plates (P28, P30, P46, and P52) selected for analysis, revealing the spatial distribution of defect intensity. The color scale represents normalized MFL signal amplitude (0–100%). With dimensions given in centimeters, the lower panels show the reconstructed scanned-track outlines. Plates 30 and 46 recorded the highest severity, with a maximum signal of 100% the upper limit of the calibrated acquisition range (5–350 mV). Plates 28 and 52 recorded a maximum signal of 86.7%, but each contains distinct white zones within the scanned surface, indicating points where the signal exceeded the acquisition range, resulting in signal saturation and loss of quantifiable data. The saturated (white) zones identified on Plates 28 and 52 were treated as high-priority zones requiring direct UT thickness verification, rather than being interpreted quantitatively from the MFL amplitude alone consistent with best practice reported in the literature. These saturated zones (Plates 28 and 52) are therefore treated as high-priority areas requiring direct UT verification.

5.1. Scanned Track Outlines

Shows the physical path actually covered by the sensor on the plate (black bands = areas effectively swept by the sensor passes). The white areas here confirm that these are zones not covered by the scan.

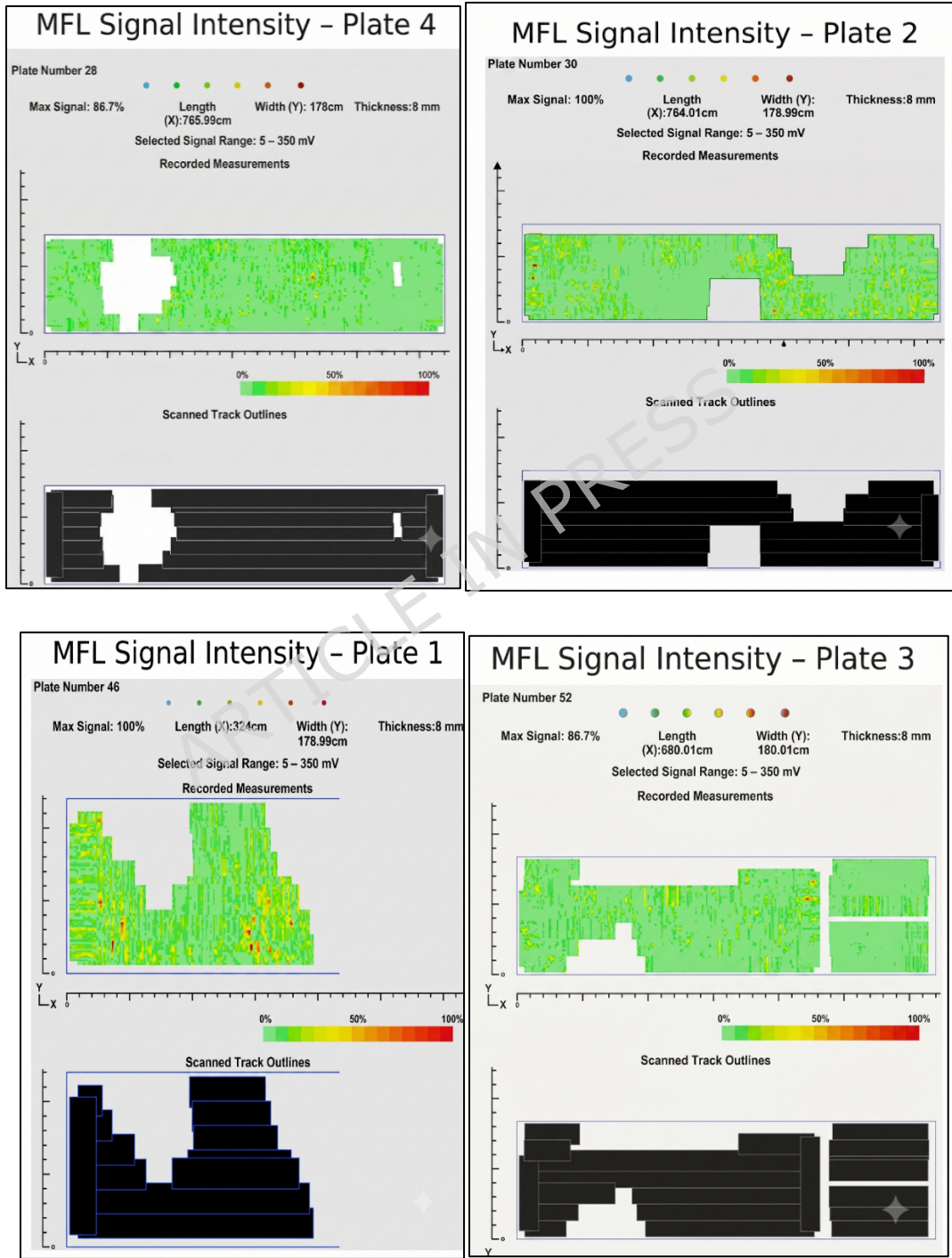


Figure 14. MFL signal intensity recorded on bottom plates.

Table 8 presents the results of thickness measurements at the locations of indications detected by MFL inspection.

Table 8. UT measurements.

Row	P	P1	P2	P3	P4	P5	MAX	MIN
R1	P1	8.86	8.45	8.62	/	/	8.86	8.45
	P2	8.7	8.6	8.54	/	/	8.7	8.54
	P3	8.33	8.28	3.79	/	/	8.33	3.79
	P4	8.8	8.31	8.58	/	/	8.8	8.31
	P5	8.26	8.72	4.49	/	/	8.72	4.49
	P6	8.39	3.27	8.26	/	/	8.39	3.27
	P7	3.67	8.2	8.83	/	/	8.83	3.67
	P8	7.76	4.34	5	/	/	7.76	4.34
	P9	5.58	7.52	4.98	/	/	7.52	4.98
	P10	4.24	4.48	0	/	/	4.28	0
	P11	2.51	8.48	6.97	/	/	8.48	2.51
R2	P12	8.17	8.28	8.37	8.5	8.55	8.55	8.17
	P13	3.28	7.38	3.65	7.71	7.78	7.78	3.28
	P14	4.42	8.23	7.23	6.28	7.84	8.23	4.42
	P15	7.71	7.6	4.29	0	0	7.71	0
R3	P16	8.47	8.53	8.85	8.24	8.32	8.85	8.24
	P17	7.8	8.08	8.48	8.31	8.09	8.48	7.8
	P18	8.32	8	2.47	4.8	7.32	8.32	2.47
	P19	2.69	7.22	0	6.08	5.04	7.22	0
	P20	7.72	3.47	0	8.01	7.26	8.01	0
R4	P21	8.06	8.4	8.53	8.32	8.41	8.53	8.06
	P22	2.98	3.06	3.84	1.85	7.34	7.34	1.85
	P23	6.54	4.46	3.82	0	4.23	6.54	0
	P24	4.48	4.2	0	0	0	4.48	0
	P25	5.68	6.26	0	0	0	6.26	0
	P26	7.3	7.45	6.63	7.62	2.06	7.45	2.06

R5	P27	8.72	8.61	7.99	8.75	8.44	8.75	7.99
	P28	6.17	8.6	5.8	6.02	4.83	8.6	4.83
	P29	7.62	2.06	7.3	7.45	6.63	7.62	2.06
	P30	8.23	8.06	0	2.75	6.47	8.23	0
	P31	7.81	0	2.9	3.03	7.32	7.81	0
	P32	0	0	3.09	6.72	7.43	7.43	0
R6	P33	8.6	8.64	8.33	8.65	8.55	8.65	8.33
	P34	8.52	8.6	8.64	8.36	8.61	8.64	8.36
	P35	8.29	8.72	4.72	8.8	8.41	8.8	4.72
	P36	6.78	8.43	3.48	5.22	6.26	8.43	3.48
	P37	7.95	0	7.41	3.3	0	7.95	0
	P38	4.48	0	3.21	7.42	0	7.42	0
R7	P39	5.99	6.33	6.45	6.32	7.21	7.21	5.99
	P40	2.39	8.55	4.93	8.49	8.3	8.55	2.39
	P41	6.87	7.42	2.28	4.64	6.06	7.42	2.28
	P42	7.16	7.67	4.58	2.72	7.39	7.67	2.72
	P43	7.48	7.69	3.4	7.23	8.6	8.6	3.4
	P44	7.33	4.74	2.25	3.38	0	7.33	0
R8	P45	8.06	4.01	7.74	8.51	1.94	8.51	1.94
	P46	7.49	7.20	6.36	7.03	5.04	7.49	5.04
	P47	8.7	8.75	8.61	8.45	8.21	8.75	8.21
	P48	8.72	7.56	7.39	7.46	2.97	8.72	2.97
	P49	8.51	3.77	8.5	4.05	2.66	8.51	2.66
	P50	8.07	3.49	2.04	5.51	3.51	8.07	2.04
R9	P51	7.5	4.49	2.63	6.78	7.01	7.5	2.63
	P52	0	0	3.48	7.26	6.7	7.26	0
	P53	8	7.74	4.5	7.31	7.19	8	4.5
R9	P59	4.48	4.39	2.78	6.21	7.46	7.46	2.78

For comparison purposes, we selected the MFL and UT thickness measurements of four plates

as illustrated in Table 9 and Table 10 shows Deviation range classification and interpretation.

Table 9. Comparison between MFL et UT measurements

Row	Plate	MFL Thickness	UT Thickness (Max)	UT Thickness (Min)	Deviation $ T_{UT} - T_{MFL} $	Relative deviation (%) $\frac{ T_{UT} - T_{MFL} }{T_{UT}} * 100$
R5	P28	6,54	8,6	4,83	1,71	35%
R6	P39	6,91	7,21	5,99	0,92	15%
R7	P46	6,72	7,49	5,05	1,67	33%
R8	P49	6,56	8,51	2,66	3,9	147%

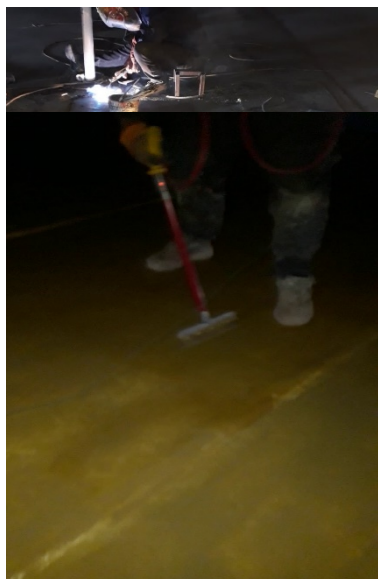
Table 10. Deviation range classification and interpretation.

Deviation range	Interpretation
< 10%	Good agreement
10% - 20%	Moderate agreement
> 20%	Significant deviation MFL not sufficiently accurate quantitatively

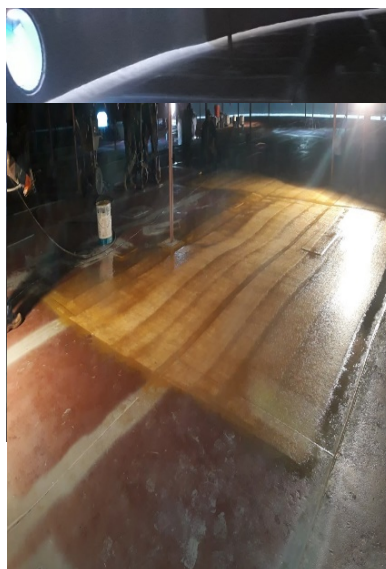
A comparison of measurement results for plates P28, P39, P46, and P49 selected using both methods reveal significant differences between the residual thicknesses estimated via MFL and UT measurements. It can be seen that on average, the MFL system overestimates the defect depth, whereas the ultrasonic method underestimates. Since UT provides a direct, localized measurement of remaining thickness, it is considered more reliable for the quantitative assessment of metal loss. Consequently, MFL can be adopted as a technique for detecting and mapping corroded areas over large surfaces, whereas UT serves as the reference method for validating defect depths and determining actual residual thickness at critical points. Based on the discrepancies observed between the two methods, the UT results were selected for decision-making and the rehabilitation of the bottom Tank A12, as illustrated by the actual repair work shown in Figure 15 (a-f)



c)
e)
Figure 15
bottom



The identified localized inner and the bottom external



d)
f)
(a-f). Repair of the
Tank A12

6. Conclusion

corrosion on Tank A12 is and affects both the outer surfaces of plates. On the surface, corrosion

is typically electrochemical in nature, initiated by the surrounding soil acting as an electrolyte. Soil corrosivity is governed by several factors, including PH, resistivity, moisture content, and the presence of chloride, sulfide, and sulfate ions, dissolved oxygen, bacterial activity, and stray currents. On the internal surface, corrosion generally originates from water that accumulates at the tank bottom. This settled water can contain highly corrosive agents such as bacteria, dissolved CO₂, salts, chloride ions, and oxygen, particularly where the protective coating is absent, degraded, or was improperly applied all of which accelerate the corrosion process.

API 653, 2020 edition, in section 4.4.5, stipulates that the minimum thickness required at the next inspection or verification must not fall below the threshold of 2.5 mm (remaining thickness). This 2.5 mm threshold applies to all critical defects found that exceed 60% metal loss relative to the nominal thickness of the bottom plates.

The defect measurements taken during the present inspection are close to or exceed the minimum required threshold as indicated in the tables above, representing 61% (99 plates). 38 plates (23%) present remaining thickness below the required threshold. Only 26 plates (16%) remain at an acceptable thickness.

The distribution of corrosion defects along the rows illustrates that 80% of defects are classified as severe, light, and concentrated in five critical rows R16, R4, R5, R18, and R3.

The analysis confirms that the corrosion of the tank remains severe despite inspections and routine visits the tank is therefore classified within the unacceptable risk zone.

Following this assessment, and in accordance with API 653 requirements, the company developed a repair plan was developed, and the rehabilitation of the tank bottom was subsequently carried out.

6.1. Recommendations

The implementation of measures is becoming increasingly important as the impact of corrosion on safety and the environment takes on more challenging roles. A heightened awareness to the

environmental impact of the use and subsequent discharge of industrial chemicals becomes necessary.

Environmental considerations could have beneficial effects on energy supply by increasing awareness of the environmental impact of energy use and, therefore, encouraging voluntary energy efficiency and the use of cleaner technologies. There are numerous methods to combat corrosion, among these methods we can cite:

- Passive prevention remains the best solution to avoid corrosion in metal installations. The most common way to prevent a metal from corroding or to delay its corrosion is to apply an impermeable coating on its surface. Unfortunately, most coatings are not perfect barriers against corrosion and therefore do not fully protect metals due to defects or the diffusion of oxygen and water through them. For all these reasons, it is necessary to use other methods of metal protection such the application of production chemicals - for example, corrosion inhibitors, scale inhibitors, biocides and demulsifiers - is now essential to the successful operation of most oil and gas fields, but with these there is the risk of their subsequent entry into the surrounding environment as corrosion inhibitors, anodic protection, and cathodic protection.
- Choosing the appropriate materials for the manufacturing of storage tanks is an important factor in the economic success of oil and gas activities.
- Carry out in-depth investigations into the circumstances of the deterioration, placing particular emphasis on the high corrosion rate to eliminate the source of deterioration and monitoring of bacterial activity.

Author Contributions

Hafida Kahoul conducted the research and review process and wrote the original draft. She was involved in obtaining, analysing, and interpreting the data for the study, as well as editing and designing the article. Mohamed Seddik Hellas and Hamza Zerrouki made contributions to obtaining, analysing, and interpreting the data for the study and revised and edited the article. Sid Ali Bacha and Rachid Chaib supervised, revised, and edited the article. Hemant Kumar and Shatrudhan Pandey assisted in the experimental work and analysis and reviewed and edited the article.

Ethical approval

This article does not contain any studies with human participants or animals performed by any of the authors.

Funding

Funding not received for this research work.

Informed consent

For this type of study, formal consent is not required.

Declaration of competing interests

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

- [1] M. Wójcik and W. Kostowski, "Environmental Risk Assessment for Exploration and Extraction Processes of Unconventional Hydrocarbon Deposits of Shale Gas and Tight Gas: Pomeranian and Carpathian Region Case Study as Largest Onshore Oilfields," *J Earth Sci*, vol. 31, no. 1, pp. 215–222, Feb. 2020, doi: 10.1007/s12583-020-1263-4.
- [2] E. Ruschel, E. A. P. Santos, and E. de F. R. Loures, "Establishment of maintenance inspection intervals: an application of process mining techniques in manufacturing," *J Intell Manuf 2018 311*, vol. 31, no. 1, pp. 53–72, Jul. 2018, doi: 10.1007/s10845-018-1434-7.
- [3] L. Leoni, F. De Carlo, N. Paltrinieri, F. Sgarbossa, and A. BahooToroody, "On risk-based maintenance: A comprehensive review of three approaches to track the impact of consequence modelling for predicting maintenance actions," *J Loss Prev Process Ind*, vol. 72, p. 104555, Sep. 2021, doi: 10.1016/j.jlp.2021.104555.
- [4] M. Hassani, R. Chaib, and R. Bouzerara, "Vulnerability Assessment for Major Industrial Risks Proposal for a Semiquantitative Analysis Method (VAMIR) Application: Oil and Gas Industry," *J Fail Anal Prev*, vol. 20, no. 5, pp. 1568–1582, 2020, doi: 10.1007/s11668-020-00960-4.
- [5] A. Hammouya, A. Kabouche, and R. Chaib, "Study of Drain Barrier Effect on Hydrocarbons Hazards," *J Fail Anal Prev 2019 195*, vol. 19, no. 5, pp. 1475–1486, Sep. 2019, doi: 10.1007/s11668-019-00748-1.
- [6] F. Ahmed and A. Fakhruddin, "A Review on Environmental Contamination of Petroleum Hydrocarbons and its Biodegradation," *Int J Environ Sci Nat Resour*, vol. 11, no. 3, 2018, doi: 10.19080/IJESNR.2018.11.555811.
- [7] N. Khan, S. Dilshad, R. Khalid, A. R. Kalair, and N. Abas, "Review of energy storage and transportation of energy," *Energy Storage*, vol. 1, no. 3, p. 49, Jun. 2019, doi: 10.1002/est2.49.
- [8] Martin H. Hilder, "Oil Storage, Transport, and Handling," in *Lipid Technologies and Applications*, New York: Routledge, 2018.
- [9] D. Keerthi Narayanan, A. Abdur Ravoof, J. Jayapriya, G. Revathi, and M. Murugan, "Hazards in oil, gas, and petrochemical industries," *Cris Oil, Gas Petrochemical Ind Disasters Environ Challenges*, pp. 71–99, Jan. 2023, doi: 10.1016/B978-0-323-95154-8.00010-4.
- [10] A. Soleymani, H. Jahangir, and M. L. Nehdi, "Damage detection and monitoring in heritage masonry structures: Systematic review," *Constr Build Mater*, vol. 397, Sep. 2023, doi: 10.1016/j.conbuildmat.2023.132402.
- [11] S. Cao, F. He, and J. Gao, "Corrosion problems in the oil country tubular goods and their mitigation – a review," *Anti-Corrosion Methods Mater*, vol. 64, no. 5, pp. 465–478, Sep. 2017, doi: 10.1108/ACMM-09-2016-1708.
- [12] K. Bhatia, F. Khan, H. Patel, and R. Abbassi, "Dynamic risk-based inspection methodology," *J Loss Prev Process Ind*, vol. 62, Nov. 2019, doi: 10.1016/j.jlp.2019.103974.

- [13] J. L. Gonzalez-Velazquez, *Mechanical Integrity and Risk-Based Inspection of Process Equipment, Piping and Pipelines*, vol. 30. Cham, Switzerland: Springer Nature Switzerland, 2024.
- [14] A. Nugroho, G. D. Haryadi, R. Ismail, and S. J. Kim, "Risk based inspection for atmospheric storage tank," *AIP Conf Proc*, vol. 1725, no. 1, Apr. 2016, doi: 10.1063/1.4945509.
- [15] S. Li and J. Li, "Condition monitoring and diagnosis of power equipment: Review and prospective," *High Volt*, vol. 2, no. 2, pp. 82–91, Jun. 2017, doi: 10.1049/hve.2017.0026.
- [16] R. W. Revie and H. H. Uhlig, *Corrosion and corrosion control*, 5th ed. John Wiley & Sons, Inc., 2025.
- [17] R. Mohamed, C. R. Che Hassan, and M. D. Hamid, "Critical success factors of risk-based inspection," *Process Saf Prog*, vol. 38, no. 1, pp. 4–20, Mar. 2019, doi: 10.1002/prs.11973.
- [18] N. Cahyono, M. B. Zaman, N. Siswanto, D. Priyanta, and T. Pitana, "Risk Analysis Using the Risk-Based Inspection (RBI) Method for a Pressure Vessel at Offshore Platform," *IOP Conf Ser Mater Sci Eng*, vol. 1052, no. 1, p. 012051, Jan. 2021, doi: 10.1088/1757-899x/1052/1/012051.
- [19] H. H. Chin, P. S. Varbanov, J. J. Klemeš, M. F. D. Benjamin, and R. R. Tan, "Asset maintenance optimisation approaches in the chemical and process industries – A review," *Chem Eng Res Des*, vol. 164, pp. 162–194, Dec. 2020, doi: 10.1016/j.cherd.2020.09.034.
- [20] M. Singh and M. Pokhrel, "A Fuzzy logic-possibilistic methodology for risk-based inspection (RBI) planning of oil and gas piping subjected to microbiologically influenced corrosion (MIC)," *Int J Press Vessel Pip*, vol. 159, pp. 45–54, Jan. 2018, doi: 10.1016/j.ijpvp.2017.11.005.
- [21] A. Campari, M. A. Darabi, F. Ustolin, A. Alvaro, and N. Paltrinieri, "Applicability of Risk-based Inspection Methodology to Hydrogen Technologies: A Preliminary Review of the Existing Standards," *Proc 32nd Eur Saf Reliab Conf ESREL 2022 - Underst Manag Risk Reliab a Sustain Futur*, pp. 574–581, 2022, doi: 10.3850/978-981-18-5183-4_R13-01-095-cd.
- [22] M. Attia and J. Sinha, "Improved quantitative risk model for integrity management of liquefied petroleum gas storage tanks: Mathematical basis, and case study," *Process Saf Prog*, vol. 40, no. 3, pp. 63–78, Sep. 2021, doi: 10.1002/prs.12217.
- [23] M. Durai, Z. Q. Lin, C. W. Lan, H. Chang, and C. C. Peng, "Study of Defects in the Petrochemical Storage Tank Floor using the Magnetic Flux Leakage (MFL) Technique," *J Fail Anal Prev*, vol. 22, no. 2, pp. 807–814, Apr. 2022, doi: 10.1007/s11668-022-01373-1.
- [24] Y. Li and C. Sun, "Research on magnetic flux leakage testing of pipelines by finite element simulation combined with artificial neural network," *Int J Press Vessel Pip*, vol. 212, Dec. 2024, doi: 10.1016/j.ijpvp.2024.105338.
- [25] A. Groysman and R. Siso, "Corrosion of Aboveground Storage Tanks Containing Fuels," *Mater Perform*, vol. 51, no. 2, pp. 52–56, Feb. 2012, doi: 10.5006/MP2012_51_2-52.
- [25] J. C. Drury and A. Marino, "A Comparison of the Magnetic Flux Leakage and Ultrasonic Methods in the Detection and Measurement of Corrosion Pitting in Ferrous Plate and Pipe," in *Proc. 15th World Conf. Non-Destructive Testing (WCNDT)*, Rome, Italy, Oct. 2000.
- [26] N. P. G. Bhavani *et al.*, "Real-Time Inspection in Detection Magnetic Flux Leakage by Deep Learning Integrated with Concentrating Non-Destructive Principle and Electromagnetic Induction," *IEEE Instrum Meas Mag*, vol. 25, no. 7, pp. 48–54, Oct. 2022, doi: 10.1109/MIM.2022.9908257.
- [27] P. PIETRO, *Monitoring and Inspections*. Cham: Springer International Publishing, 2018.
- [28] D. Slesarev, "Defect identification based on wavelet decomposition for MFL non-destructive

inspection of steel plates,” *Insight Non-Destructive Test Cond Monit*, vol. 63, no. 3, pp. 146–150, Mar. 2021, doi: 10.1784/insi.2021.63.3.146.

- [29] Z. Ren, F. Fang, N. Yan, and Y. Wu, “State of the Art in Defect Detection Based on Machine Vision,” *Int J Precis Eng Manuf - Green Technol*, vol. 9, no. 2, pp. 661–691, Mar. 2022, doi: 10.1007/s40684-021-00343-6.

ARTICLE IN PRESS